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ACOUSTIC PROCESSING FOR ESTIMATING SIZE OF SMALL TARGETS

TO ALL WHOM IT MAY CONCERN:

BE IT KNOWN THAT ANTHONY A. RUFFA, citizen of the United States of America, employee of the United States Government and resident of Hope Valley, County of Washington, State of Rhode Island has invented certain new and useful improvements entitled as set forth above of which the following is a specification:

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James M. Kasischke  
APPLICANT'S ATTORNEY

7 August 2003  
DATE OF SIGNATURE

1 Attorney Docket No. 82781

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3 ACOUSTIC PROCESSING FOR ESTIMATING SIZE OF SMALL TARGETS

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5 STATEMENT OF GOVERNMENT INTEREST

6 The invention described herein may be manufactured and used  
7 by or for the Government of the United States of America for  
8 Governmental purposes without the payment of any royalties  
9 thereon or therefor.

10

11 CROSS REFERENCE TO OTHER PATENT APPLICATIONS

12 Not applicable.

13

14 BACKGROUND OF THE INVENTION

15 (1) Field of the Invention

16 The present invention relates generally to acoustic  
17 processing, and more particularly to an acoustic processing  
18 method that can be used to estimate the size of small objects in  
19 a fluid medium.

20 (2) Description of the Prior Art

21 It is difficult to generate an image of an object using  
22 acoustic echoes when the object size is on the order of the  
23 wavelength of the acoustic radiation used to generate the  
24 echoes. At lower frequencies, or smaller sizes, scattering

1 becomes less "specular" and more "diffracting" in nature. While  
2 there have been some successful efforts involving the imaging of  
3 small objects in the near field, the technique cannot be  
4 extended to the imaging of small objects in the far field. If  
5 such far field imaging could be achieved, it could be used in  
6 medical acoustic, sonar, and particle detection on semiconductor  
7 wafer evaluation applications. In each of these applications,  
8 it may also be desirable to know the size of the small object,  
9 e.g., a tumor or other physical abnormality in medical acoustic  
10 applications, a mine-like object in sonar applications, and an  
11 imperfection in a semiconductor in wafer evaluation  
12 applications.

#### 14 SUMMARY OF THE INVENTION

15 Accordingly, it is an object of the present invention to  
16 provide a method of acoustic processing that can be used to  
17 estimate the size of a small object.

18 Another object of the present invention is to provide a  
19 method of acoustic processing that can be used to estimate the  
20 size of an object that is smaller than one to two wavelengths of  
21 the acoustic radiation directed towards the object for the  
22 purpose of generating reflections or echoes therefrom.

1        Still another object of the present invention is to provide  
2        a method that uses only a single orientation of a sensor array  
3        to estimate the size of a small object.

4        Other objects and advantages of the present invention will  
5        become more obvious hereinafter in the specification and  
6        drawings.

7        In accordance with the present invention, a method for  
8        estimating the size of an object begins with monitoring acoustic  
9        radiation originating from a region of a fluid medium using a  
10       line array of  $N$  acoustic receivers such that  $N$  signals  
11       indicative of the acoustic radiation are generated. It is  
12       assumed that the acoustic radiation has a known wavelength  $\lambda$ .  $M$   
13       time series summations are formed using the  $N$  signals. Each of  
14       the  $M$  time series summations is formed using a unique time delay  
15       predicated on a corresponding unique estimated speed of  
16       propagation of the acoustic radiation where  $M$  estimated speeds  
17       of propagation are defined. A temporal Fourier transform is  
18       performed on each of the  $M$  time series summations to generate  $M$   
19       values. For an object in the region having a diameter  $D < 2\lambda$ , the  
20        $M$  values will vary as a function of the  $M$  estimated speeds of  
21       propagation. The resulting distribution of the  $M$  values are  
22       indicative of diameter  $D$ .

1 BRIEF DESCRIPTION OF THE DRAWINGS

2 Other objects, features and advantages of the present  
3 invention will become apparent upon reference to the following  
4 description of the preferred embodiments and to the drawings,  
5 wherein corresponding reference characters indicate  
6 corresponding parts throughout the several views of the drawings  
7 and wherein:

8 FIG. 1 is a diagrammatic view of an acoustically opaque  
9 screen having a two dimensional aperture formed therethrough  
10 where the screen is subjected to a planar acoustic wave on one  
11 side thereof to illustrate the propagation of the acoustic  
12 radiation passing through the aperture on the other side of the  
13 screen;

14 FIG. 2 is a schematic view of a line array of acoustic  
15 receivers used to detect acoustic radiation originating from  
16 targets located in both the end fire beam of the array and in  
17 beams away from end fire;

18 FIG. 3 is a flowchart of the method of the present  
19 invention;

20 FIG. 4A is a schematic view of a first embodiment of a  
21 system for processing the acoustic radiation received by the  
22 receivers in FIG. 2 in accordance with the present invention;  
23 and

1        FIG. 4B is a schematic of a second embodiment of a system  
2        for processing the acoustic radiation received by the receivers  
3        in FIG. 2 in accordance with the present invention.

#### 5                    DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

6        Before describing the method of the present invention, it  
7        will be beneficial to describe some background concepts on which  
8        the present invention is predicated. Referring now to the  
9        drawings, and more particularly to FIG. 1, an infinite,  
10        acoustically opaque screen is referenced by numeral 10. Screen  
11        10 has an aperture 12 formed therethrough. On one side of  
12        screen 10, an acoustic source 14 propagates a planar acoustic  
13        wave 16 towards screen 10. If the diameter of aperture 12 is  
14        small (e.g., on the order of the wavelength of acoustic wave  
15        10), acoustic wave 16 diverges as it passes through aperture 12  
16        to form diverging waves 18-1, 18-2, ... traveling at a range of  
17        velocities. The slowest velocities are found in the diverging  
18        waves moving approximately parallel to screen 10 (e.g., wave 18-  
19        1) and the fastest velocities are found in the diverging waves  
20        moving approximately perpendicular to screen 10 (e.g., wave 18-  
21        4).

22        The method of the present invention takes note of the fact  
23        that an exact solution for (acoustic wave) diffraction of a two-  
24        dimensional aperture in an infinite screen is given as

$$p(x, y, z, t) = \frac{e^{-i\omega_0 t}}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F(k_x, k_y) e^{-ik_x x} e^{-ik_y y} e^{iz\sqrt{k^2 - k_x^2 - k_y^2}} dk_x dk_y \quad (1)$$

See G.C. Gaunard et al., J. Acoust. Soc. Am., Vol. 63, p. 5, 1978. In equation (1),  $p$  is the acoustic pressure,  $F(k_x, k_y)$  is the two-dimensional spatial Fourier transform in the screen that is in the X-Y plane, and  $k$  is the propagation wavenumber in the  $z$  direction. This equation solves the governing equation exactly and meets all boundary conditions.

The above diffraction integral can be evaluated using the generalized method of exhaustion to more clearly see the behavior of each component using the following

$$\int_0^b f(x) dx = b \sum_{n=1}^{\infty} \sum_{m=1}^{2^n-1} (-1)^{m+1} 2^{-n} f(mb/2^n) \quad (2)$$

This method of exhaustion is disclosed by A.A. Ruffa, International Journal of Mathematics and Mathematical Sciences 31(6), 8 August 2002, p. 345. Note that propagating waves will only occur when the transverse wavenumber  $(k_x^2 + k_y^2)^{1/2}$  is lower than the cutoff wavenumber, so the integral can be evaluated to  $\pm k$  with good accuracy (assuming that  $F(k_x, k_y)$  is an even function with respect to both  $k_x$  and  $k_y$ ) as follows

$$p(x, y, z, t) = \frac{2k^2}{\pi} e^{-i\omega_0 t} \sum_{n=1}^{\infty} \sum_{m=1}^{2^n-1} \sum_{p=1}^{\infty} \sum_{q=1}^{2^p-1} (-1)^{m+q} 2^{-n-p} \left( \frac{mk}{2^n}, \frac{qk}{2^p} \right) e^{-imxk2^n} e^{-iqyk2^p} e^{izk\sqrt{k^2 - m^2/4^n - q^2/4^p}} \quad (3)$$

1        From this expression, it can be shown that the resulting  
2 field is due to a summation of an infinite number of  
3 contributions (e.g., waves 18-1, 18-2, ...), each propagating at a  
4 different phase speed (and hence a different group speed) based  
5 on its value of  $k_x$  and  $k_y$ .

6        The acoustic field radiating from such an aperture will  
7 have a continuous range of velocities, the amplitude  
8 distribution of which will depend on the Fourier transform of  
9 the field at the aperture  $F(k_x, k_y)$ . For example, if the field  
10 scattered from acoustic source 14 is replaced by plane wave of  
11 infinite extent,  $F(k_x, k_y)$  becomes a Dirac delta function and the  
12 velocity distribution reduces to that of a single velocity.  
13 If, on the other hand, the aperture is very small compared to a  
14 wavelength, then  $F(k_x, k_y)$  will be nearly constant up to the  
15 cutoff wavenumber and the propagation velocity distribution will  
16 be much larger.

17        In equation (3), the aperture will radiate propagating  
18 waves 18-1, 18-2, ... as long as  $k^2 \geq k_x^2 + k_y^2$  (the cutoff  
19 wavenumber). For spanwise wavenumbers  $k_x$  and  $k_y$  that do not meet  
20 this condition, the resulting field will not propagate, but  
21 rather will be a decaying evanescent field.

22        The phase speed will increase from  $c$  at the zero spanwise  
23 wavenumber to infinity at the cutoff wavenumber. The group  
24 speed, however, will decrease from  $c$  to zero at the cutoff

1 wavenumber. The group speed is independent of range and is  
2 given as

$$c_g = c \sqrt{1 - (k_x^2 + k_y^2) / k^2} \quad (4)$$

6 Large decreases in group speed will lead to increased Doppler  
7 shifts. This can be potentially useful for low-Doppler targets.  
8 Also, if the velocity distribution of the acoustic field  
9 (associated with waves 18-1, 18-2, ...) can be measured, it will  
10 be directly related to  $F(k_x, k_y)$ , and therefore provide  
11 information on the effective size of aperture 12.

12 The present invention provides a method for estimating the  
13 size of a small object in a fluid medium using the principles  
14 described above. To explain the present method, reference will  
15 be made to FIG. 2 where two small objects 20 and 22 are assumed  
16 to reside in a fluid (e.g., water) medium. A linear (or line)  
17 array 30 of acoustic receivers are placed in the fluid medium.  
18 As illustrated, object 20 lies in the end fire region of array  
19 30 and object 22 lies in region away from the end fire of array  
20 30.

21 The number of receivers used is not a limitation of the  
22 present invention. In general, N acoustic receivers will be  
23 discussed herein. Each of receivers 32-1 to 32-N is capable of  
24 passively detecting acoustic radiation (waves) 21 and 23

1 originating from each of objects 20 and 22, respectively.  
2 Typically, acoustic radiation 21 and 23 is representative of  
3 acoustic reflections caused when an acoustic source 24 transmits  
4 acoustic radiation 25 of a known wavelength into the region(s)  
5 in which objects 20 and 22 reside. However, it is to be  
6 understood that use of acoustic source 24 is not a requirement  
7 or limitation of the present invention.

8       The present invention will first be described for  
9 estimating the size of object 20 lying in the end fire region of  
10 array 30. The N signals detected by N-channel array 30 are  
11 indicative of acoustic radiation (reflections) 21. The  
12 continuously received signals are sampled at a time based on the  
13 relative location of each acoustic receiver in array 30 and the  
14 speed of propagation of acoustic radiation (reflections) 21.  
15 For the end fire situation, acoustic receiver 32-1 is sampled at  
16 a time  $t$  and each successive receiver is sampled at a time  
17 delayed from  $t$  where the time delay is a function the distance  $d$   
18 from acoustic receiver 32-1 and the speed of propagation of  
19 acoustic radiation (reflections) 21.

20       Based on the concepts for an aperture in an infinite screen  
21 described above, the speed of propagation of radiation  
22 (reflections) 21 will be a distribution of speeds if the size of  
23 object 20 is on the order of the wavelength of acoustic  
24 radiation (reflections) 21. More specifically, if object 20 has

1 a diameter D that is less than approximately twice the  
2 wavelength of acoustic radiation (reflections) 21, there will be  
3 a distribution of propagation speeds that is indicative of the  
4 size of object 20. In its simplest form, the present invention  
5 assumes or approximates a circular shape for object 20.  
6 However, it is to be understood that the invention can be used  
7 to approximate other shapes for object 20 at the expense of more  
8 complicated processing.

9 Assuming the size of object 20 is on the order of the  
10 wavelength of acoustic radiation (reflections) 21, the present  
11 invention determines the distribution of the speed of  
12 propagation associated therewith. To do this, M different  
13 speeds of propagation are estimated and used in the processing  
14 of the sampled signals from array 30. The M different speeds  
15 define a range of distribution of speeds that acoustic radiation  
16 (reflections) 21 are expected to exhibit for the size of an  
17 object (e.g., object 20) of interest.

18 In FIG. 3, there is shown a flowchart providing the method  
19 34 of using this invention. This flowchart is made for the  
20 embodiment in which an acoustic signal (25 in FIG. 2) is  
21 transmitted toward an object (20 or 22 in FIG. 2) in step 36 and  
22 reflects (21 or 23 in FIG. 2) from the object. Step 36 can be  
23 omitted when the object is radiating an acoustic signal at a  
24 known wavelength. The acoustic signal is received 38 at an

1 array of sensors 30. The received signal at each sensor is  
2 processed 40 in parallel. In one embodiment, the step of  
3 processing 40 can be merely forming an amplitude sum of the  
4 signals received at each sensor. This is further detailed in  
5 the discussion of FIG. 4A below. In another embodiment, the  
6 step of processing 40 can be forming an amplitude sum of the  
7 signals and then performing a temporal Fourier transform of the  
8 signals. This is further detailed in the discussion of FIG. 4B  
9 below. In either case, processing 40 accounts for the  
10 orientation of the array 30 and the spacing of sensors 32-1  
11 through 32-N while calculating the amplitude sum. In step 44,  
12 the invention determines if velocity spreading exists in the  
13 amplitude sums. If velocity spreading does not exist, the  
14 object must be larger than two wavelengths ( $2\lambda$ ), and a different  
15 method must be used to determine size. If velocity spreading  
16 does exist, a database of known object data 48 can be compared  
17 in step 50 with the amplitude sums and the Fourier transforms to  
18 give information about the object. In the most basic case, the  
19 known object database 48 contains data from disks having a range  
20 of diameters below the two wavelengths limit. In a more  
21 complicated case, the know object database 48 contains objects  
22 having a variety of different shapes, sizes and orientations.  
23 These objects can be disks, spheres or cylinders. The  
24 comparison step 50 provides an output of the diameter of the

1 object, the object's shape, and/or the object's orientation.  
2 Output is provided in step 52 to a user or to another system.  
3 Processing of the  $N$  sampled signals  $s_i$  for  $i = 1$  to  $N$  is  
4 carried out as illustrated in FIGs. 4A and 4B where parallel  
5 processing (e.g., by individual processors or one parallel  
6 processor) improves processing efficiency; however, sequential  
7 processing can be used. Each of  $M$  processors 40-1, ..., 40- $M$   
8 forms a sum  $V(t)$  of the time sampled signals  $s_i$  where the first  
9 term in each summation is the signal sampled at acoustic  
10 receiver 32-1 at time  $t$  and each successive  $i$ -th term is delayed  
11 by  $(2\pi d_i/c_m)$  where  $d_i$  is the distance from the  $i$ -th receiver to  
12 receiver 32-1,  $c_m$  is an estimated speed of propagation for the  $m$ -  
13 th processor, and  $f$  is the frequency of acoustic radiation  
14 (reflections) 21. Each of the resulting  $M$  time series  
15 summations (e.g., voltage signals  $V_m(t)$ ) for  $m = 1$  to  $M$  can have  
16 (as illustrated by the FIG. 4B embodiment) a temporal Fourier  
17 transform applied thereto at 42-1, ..., 42- $M$  as a measure of the  
18 Doppler shift  $\Delta f$ . Lower speeds of propagation lead to increased  
19 Doppler shifts. The Doppler shift measurements are an  
20 independent check on each propagation velocity.

21 An amplitude distribution as a function of speed of  
22 propagation  $c_m$  for  $m = 1$  to  $M$  indicates the presence of a "small"  
23 target. Conversely, little or no velocity spread is indicative  
24 of the fact that no "small" targets are present in the region of

1 interest. Assuming there is a velocity distribution, the actual  
2 amplitude (voltage) distribution as a function of  $c_m$  is used to  
3 estimate the size of object 20 as follows. The measured  
4 distribution is compared to a plurality of two-dimensional  
5 spatial Fourier transform distributions determined for a  
6 corresponding plurality of known-dimension, circular apertures  
7 in infinite acoustically-opaque screens. The aperture size of  
8 the spatial Fourier transform distribution that most closely  
9 matches the measured/determined amplitude distribution (vs.  $c_m$   
10 approximates a (circular shape) size of object 20.

11 For object 22 that resides away from the end fire of array  
12 30, processing in each beam of array 30 would proceed the same  
13 as described above so that the amplitude would again be  
14 estimated for each of the M estimated speeds of propagation  $c_m$ .  
15 Away from end fire, the effect of a distribution of propagation  
16 speeds is exhibited as a "beam spreading" effect where slower  
17 acoustic velocities lead to signals in adjacent beams. Beam  
18 spreading also occurs due to multipaths, which would show up in  
19 adjacent beams closer to broadside. In active sonar (e.g.,  
20 where acoustic source 24 provides acoustic radiation that  
21 generates reflections 21), the main path could be identified as  
22 the one arriving first. As is known in the art, this can be  
23 accomplished with replica correlator processing. Multipaths  
24 would appear in adjacent beams closer to broadside while any

1 velocity distribution would lead to adjacent beams further away  
2 from broadside and involving velocities slower than the speed of  
3 propagation in the main path. The resulting Doppler shifts  
4 would be increased in adjacent beams due to the slower acoustic  
5 velocity in the beam. Since this would not occur as a result of  
6 multipaths, it provides a method to distinguish between beam  
7 spreading due to a velocity distribution with that due to  
8 multipaths.

9 The advantages of the present invention are numerous.  
10 Small underwater targets can have their size estimated. Such  
11 size estimation is an important clue used in target  
12 classification.

13 It will be understood that many additional changes in the  
14 details, materials, steps and arrangement of parts, which have  
15 been herein described and illustrated in order to explain the  
16 nature of the invention, may be made by those skilled in the art  
17 within the principle and scope of the invention as expressed in  
18 the appended claims.

2

3 ACOUSTIC PROCESSING FOR ESTIMATING SIZE OF SMALL TARGETS

4

5 ABSTRACT OF THE DISCLOSURE

6 A method is provided for estimating the size of an object  
7 from a region of a fluid medium when that object is emitting  
8 acoustic radiation of known wavelength  $\lambda$  on its own or as the  
9 result of being interrogated by acoustic pulses that reflect  
10 from the object. The acoustic radiation is monitored using a  
11 line array of N acoustic receivers such that N signals  
12 indicative of the acoustic radiation are generated. M time  
13 series summations are formed using the N signals. Each of the M  
14 time series summations is formed using a unique time delay  
15 predicated on a corresponding unique estimated speed of  
16 propagation of the acoustic radiation where M estimated speeds  
17 of propagation are defined. For an object in the region having  
18 a diameter D on the order of  $\lambda$ , the M values will vary as a  
19 function of the M estimated speeds of propagation with the  
20 resulting distribution of the M values being indicative of  
21 diameter D.

FIG. 1

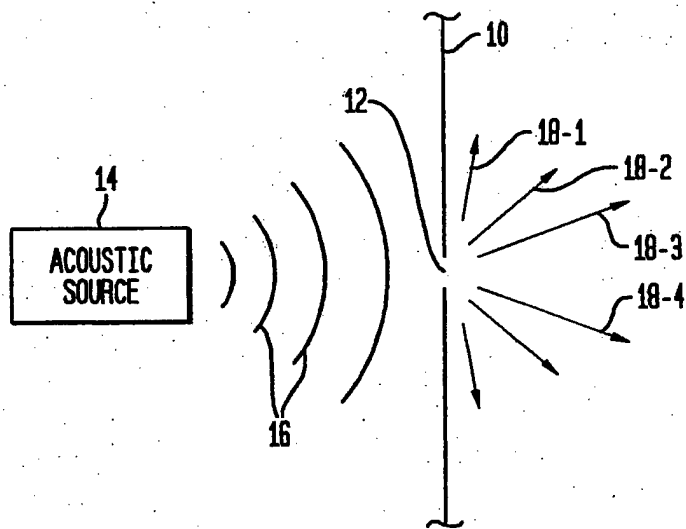


FIG. 2

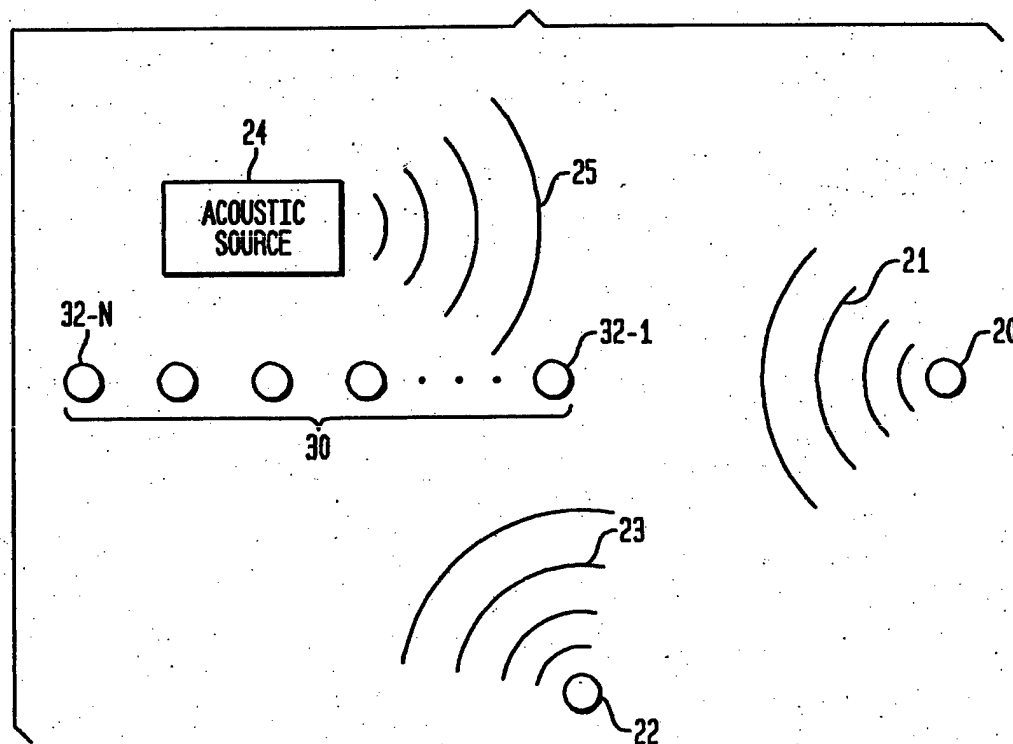


FIG. 3

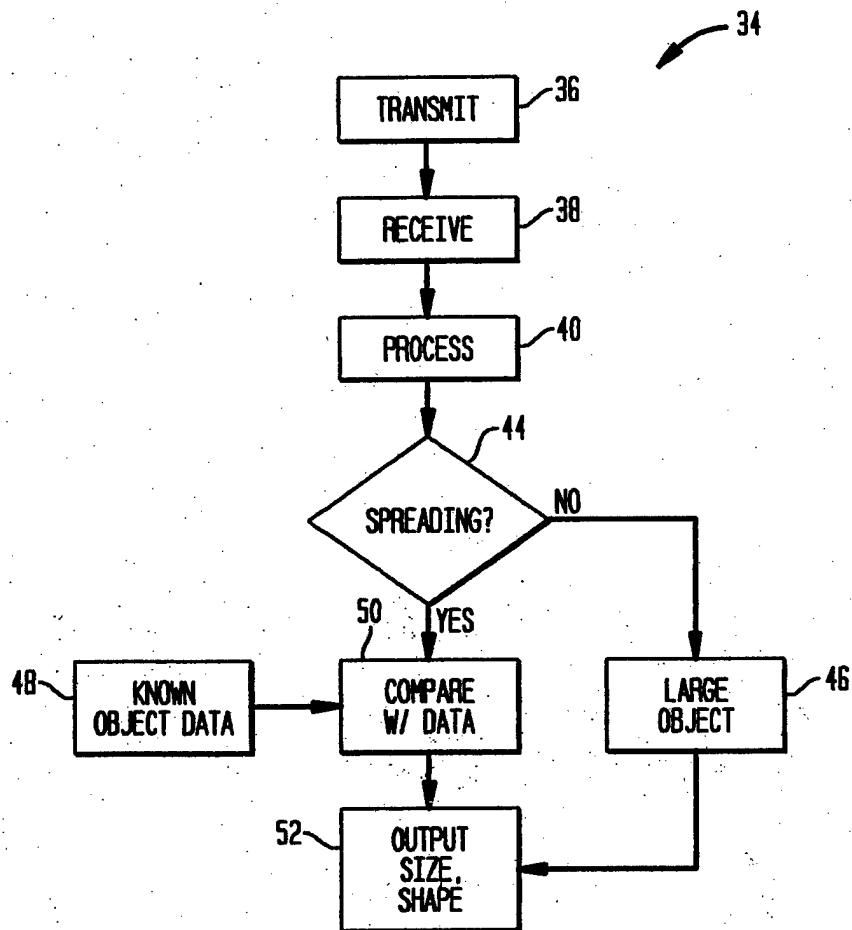


FIG. 4A

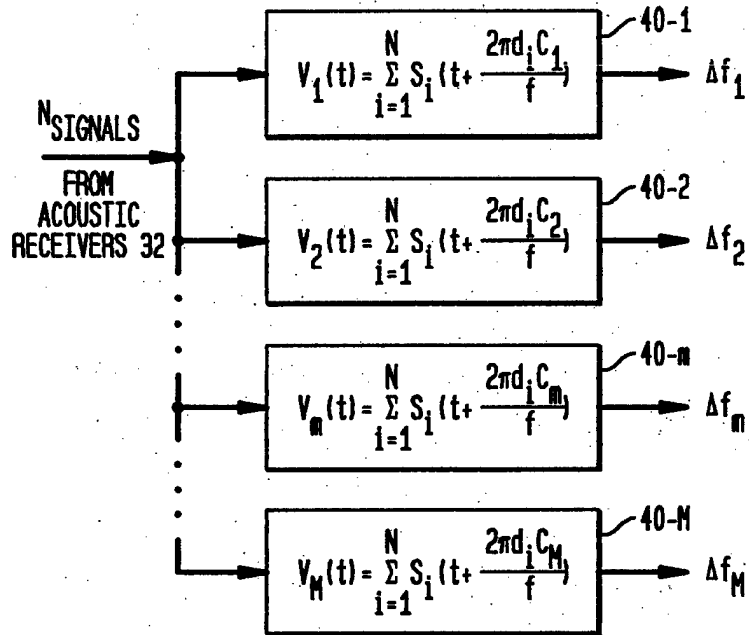


FIG. 4B

